Cooperative Research and Development Agreement Final Report

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Parties to the Agreement: Princeton Plasma Physics Laboratory and Helion Energy, Inc.

CRADA number: PPPL-2722

CRADA Title: Nonlinear kinetic simulation study of non-equilibrium and merging FRCs

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Sponsoring DOE Program Office(s): FES

Executive Summary of CRADA Work:

The Cooperative Research and Development Agreement (CRADA) between Princeton Plasma Physics Laboratory (PPPL) and Helion Energy, Inc. focused on numerical studies of FRC merging and non-equilibrium stability of translating and merging FRCs. The hybrid version of the HYM code with fluid electrons and kinetic thermal ions was used to model FRC translation, merging and compression. In simulation, FRC parameters and profiles were varied to study their effects on the merging process. Hybrid simulation results were also compared with results of the MHD simulation to evaluate the importance of kinetic effects. In cases without magnetic compression, both the MHD and hybrid simulations show a high sensitivity of the results to the initial parameters: FRC separation, velocity, normalized separatrix radius and plasma viscosity, showing that FRCs with large elongation and separatrix radius either do not merge or merge partially, forming a doublet FRC. Application of mirror coil field at the FRC ends with increasing strength is shown to lead to fast and complete merging of the FRC in MHD and kinetic simulations. Understanding the physics of the FRC merging, its dependence on the plasma parameters, and scaling with the device size is important for achieving the goals of the Helion experimental program and planning of the next-generation fusion plant prototype. In this public-private partnership, scientific contributions from the Department of Energy directly contributed to the acceleration of progress toward the development of fusion energy in the private sector.

Summary of Research Results:

BACKGROUND

An improved understanding of FRC merging and stability in high acceleration and compression magnetic fields is needed to speed up the development of the pulsed fusion concept developed at Helion Energy. Previous theoretical and simulation work on FRC merging and compression was performed using 2D MHD models. Since the MHD instabilities in FRCs are stabilized or partially stabilized in the kinetic regimes, hybrid simulations (fluid electrons and full-orbit kinetic ions) of FRCs are needed for a realistic description of the experiments. In this project, 2D and 3D kinetic simulations have been performed using the HYM code, and the kinetic results have been compared with MHD simulations. The comparison is then used to evaluate the importance of the ion kinetic effects.

TECHNICAL DISCUSSION OF WORK PERFORMED

1. 2D FRC merging simulations

Initial conditions in the HYM code have been modified for FRC merging simulations, including different initial velocity and pressure profiles, and a set of 2D hybrid simulations have been performed to check the effects of the initial conditions on the FRC merging. It was shown that without magnetic compression, the FRC merging is very sensitive to initial parameters, including the separatrix beta, normalized separatrix radius, $x_s = R_s/R_c$, and the initial separation of the FRCs. Larger values of these parameters are found to be generally unfavorable for the merging. For example, increasing the separatrix beta from $\beta_s = 0.2$ to 0.3 for $x_s \sim 0.7$ resulted in failure to merge, and the FRCs eventually drifting apart. The sensitivity to these parameters is explained by the finite plasma density present in the open field line region between the FRCs. In addition, it has been shown that without compression FRCs with larger elongation ($E > 3$) and a relatively large separatrix radius ($x_s \sim 0.7$) merge partially forming a doublet in both the MHD and kinetic simulations. A simple analytic model has been developed to explain the sensitivity of the FRC merging simulation results to the initial conditions (initial FRC velocity, separation, and relative separatrix radius). Hybrid simulations of the FRC merging performed for the Helion FRC's parameters show partial FRC merging, similar to MHD simulation results. The simulations show that the FRC kinetic parameter, S*, does not change significantly during the merging. The FRC elongation after the merging was increased by a factor ~ 2.3 in the cases of partial merging (doublet FRC). For the complete merging, the elongation increase is found to be by a factor of ~ 1.7. Considering that the tilt mode stability favors smaller values of S^*/E parameter, the FRC merging is beneficial for the tilt stability.

A set of new time-dependent boundary conditions has been implemented in the MHD and hybrid versions of HYM code to study the FRC merging under compression. Both 2D MHD simulations of a single FRC compression, and simulations of two FRC merging during compression have been performed. Several simulations of merging and compression have been performed with different radial and axial resolutions to demonstrate the convergence of the results. Comparison between hybrid and MHD simulations for Helion parameters shows similar global dynamics and comparable time scales. It was shown that the axial compression by the increasing mirror magnetic fields at the FRC ends results in faster and more complete merging of the FRCs. In that case, the FRCs merge fully on a time scale of $t \sim 20 - 25t_A$ in both the MHD and hybrid simulations. High-resolution hybrid and MHD simulations were performed for comparisons of the details of the reconnection physics during the FRC merging, focusing on the details of the reconnection, global dynamic time scales, and relaxation of the FRC after the merging. A paper on the FRC merging simulations was submitted to Fusion Science and Technology journal (for INFUSE-related paper collection).

2. **FRC translation**

Initial and boundary conditions in HYM code were modified to perform MHD and hybrid simulations of the FRC acceleration and translation. FRC was accelerated by gradually increasing mirror field on one side by 50%. The FRC reached a peak axial velocity of $0.5V_A$ in $t{\sim}15t_A$ in both hybrid and MHD simulations. FRC motion in axial direction in hybrid runs was similar to MHD, despite particle losses at the FRC ends, plasma spin-up in toroidal direction, and generation of a finite toroidal magnetic field in kinetic simulations. The main differences between the 2D hybrid and the MHD simulations were an excitation of short wavelength oscillations in the kinetic simulations and larger FRC velocities after the peak acceleration, possibly due to an open-field line particle loss and density reduction. Plasma heating was observed on the compression side.
3D simulations of FRC translation were performed to investigate FRC stability with respect to global MHD modes for different translation velocities. In the MHD simulations, starting with a random initial perturbation, the most unstable MHD modes were the modes with the highest resolved toroidal mode numbers (n=4-5, for the case considered), which is consistent with MHD linear stability predictions. Larger FRC translation velocities were found to be destabilizing in the MHD regime, with the FRC lifetimes decreasing from $t{\sim}20t_A$ to $t{\sim}12t_A$ as the initial translation velocity was increased from v=0 to $v=0.5v_A$. Initial 3D hybrid simulations of FRC acceleration and translation for S*~20 show significantly reduced growth rates, dominant n=1 mode, and excitation of small-scale oscillations.

3. **3D simulations of translating and merging FRCs**

Domain decomposition in HYM code has been modified to allow an increased simulations grid for 3D high-resolution hybrid simulations of FRC merging. The new version of the code has been benchmarked against previous 2D simulations. Initial 3D hybrid simulations of FRC merging were performed for cases without the magnetic compression, showing FRC merging and growth of the n=1 tilt mode for the initial FRC parameters: S*~25 and S*/E~8, which is relatively close to the MHD regime. A comparison with 3D WarpX simulations for smaller S* was initialized aiming to reproduce the same initial conditions, FRC parameters and the magnetic compression geometry, which required implementation of new boundary conditions in the HYM code modeling the magnetic field coils parameters and time sequence for a comparison with WarpX simulations.

4. POTENTIAL APPLICATIONS, TECHNOLOGY TRANSFER

The completed work has identified key parameters for efficient FRC merging. Experimental and engineering impacts include the opportunity to experimentally validate theoretical predictions, and to potentially achieve higher performance plasmas. The above impacts will also feed into the design of the future FRC merging and compression experiments and development, verification and validation of numerical simulation tools. This would bring a very large mitigation of technical and financial risk.

5. List of presentations, publications; code development; models

1. Paper: "Hybrid simulations of FRC merging and compression" by E. Belova, S.E. Clark, R. Milroy et al., has been submitted to Fusion Science and Technology journal.
2. Poster presentation "Hybrid simulations of FRC merging and compression" at the APS DPP Meeting, Atlanta GA, 2024.
3. Several new options have been developed and implemented in the HYM code during this study: a) Modified initial conditions in the HYM code to study the FRC merging; b) Implemented several sets of time-dependent boundary conditions to model FRC translation and compression; c) Modified domain decomposition in the HYM code to increase simulation grid for higher resolution and 3D hybrid simulations of FRC merging.

6. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

This project contributes to a broader understanding of the conditions needed for more efficient FRC merging and compression. It also contributes to the development and benchmarking of numerical codes suitable for modeling highly dynamical merging and compression of FRCs. The project also strengthens the collaboration between Helion Energy, Inc. and PPPL, benefiting both parties by cross-fertilization of ideas and code benchmarking.